Missouri River Updated Stage-Frequency Below Rulo, Nebraska

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Abstract

The Kansas City District of the U. S. Army Corps of Engineers has updated the stage-frequency profiles for the Missouri River from Rulo, Nebraska, downstream to the confluence with the Mississippi River. Recently revised flow-frequency values were used in the development of the updated profiles. For hydraulic modeling, period of record inflow hydrographs were routed using the unsteady flow program UNET with current geometry conditions. The stage-discharge relationship at each cross section was determined using the computed annual maximum values for stage and flow. Statistical analysis combined flow-frequency values and the stage-discharge relationship to determine stage-frequency values at every Missouri River cross section. The methodology and mechanics of the development of stage-frequency profiles in the Kansas City District are discussed. Steps in the stage-frequency analysis are outlined. Topics include data requirements, development of the UNET model, period of record analysis, and water surface profile analysis.

Introduction

Water surface profiles currently in use for the Missouri River downstream of Rulo, Nebraska, were developed from frequency flows developed in the 1960's and stage-frequency relationship estimates developed in the 1970's by the Kansas City District of the U. S. Army Corps of Engineers. Since that time, new computer programs and methodologies have been developed. Thirty to forty more years of discharge and stage data are available, which includes several major flood events on the Missouri River. The Upper Mississippi River System Flow Frequency Study (UMRSFFS) was initiated to update the flow frequency and stage frequency estimates for the major rivers in the Mississippi River Basin, including the Missouri River. The UMRSFFS technical studies began in 1998 and will be completed in May 2003. This paper explains tasks and methods used by the Kansas City District for stage-frequency analysis and development of new water surface profiles utilizing the computer program UNET.

Study Area Description

The Kansas City District developed a UNET computer model of the Missouri River from Rulo, Nebraska, at River Mile (RM) 498.1, downstream to the Missouri River's confluence with the Mississippi River. The total drainage area of the Missouri River Basin is 525,400 square miles. The Missouri River drainage area within the Kansas City District is 110,500 square miles. Figure 1 is a schematic of the Missouri River in the Kansas City District. The schematic shows Missouri River gaging stations on the mainstem with river mile location plus basin drainage areas at those gages. It also shows the tributaries that are routing reaches in the UNET model, and the tributary gaging stations.

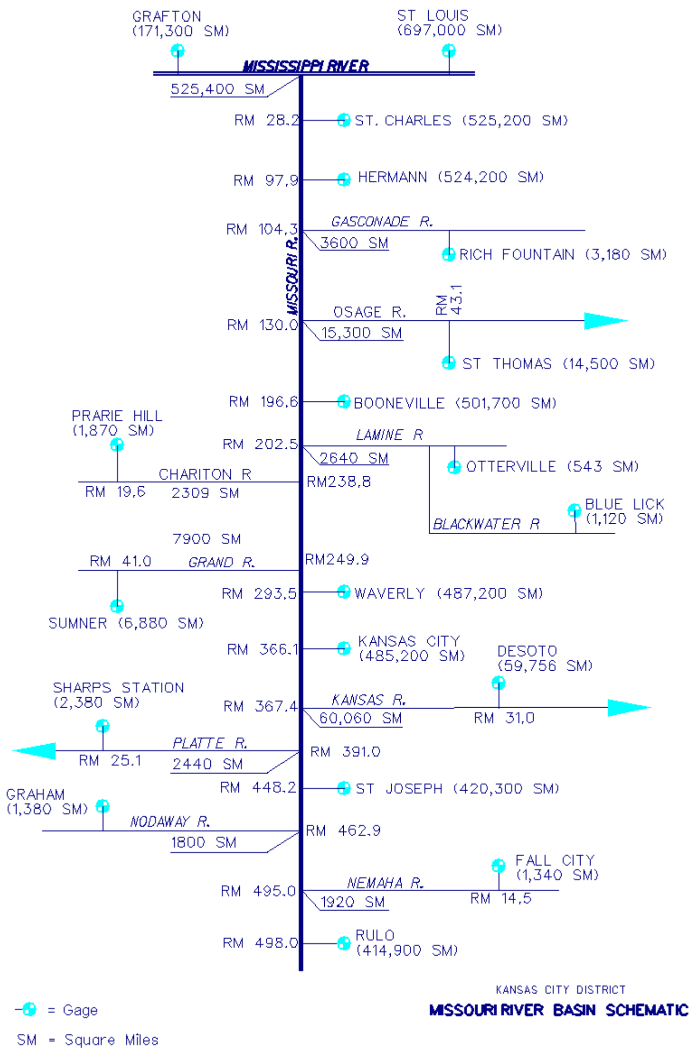

Figure 1. Schematic of the Missouri River Basin in the Kansas City District

UNET Hydraulic Model

UNET is the unsteady flow hydraulic analysis computer program selected and used for the UMRSFFS. Dr. Robert L. Barkau is the author and developer of the UNET computer program. The U. S. Army Corps of Engineers Hydrologic Engineering Center (HEC) maintains, distributes, and supports the standard version of UNET for Corps of Engineers' offices. In order to facilitate simulation of the Missouri River system within the Kansas City District, Dr. Barkau developed a specialized version of UNET for this study.

UNET is a one-dimensional, unsteady open-channel flow computer model program that can simulate flow in single reaches or complex networks of interconnected reaches. Simulation of storage areas, which are also called storage cells, is a feature of UNET. Storage areas are lake-like regions that can either divert water from, or provide water to, a river or channel. Therefore, this feature can be used to simulate the interaction of a river with levees (Barkau 1992 and UNET User's Manual 2001). The UMRSFFS is the first time this type of unsteady flow model has been used on a major river to produce water surface profiles for various flood frequencies.

Data Requirements.

Gage Data. Recorded gage data was acquired at all Missouri River gage locations. Tributary gage data was obtained for the last downstream streamflow gage for each tributary in the model. Discharge and stage hydrographs for the Missouri River and tributaries are required for inflow, boundary conditions, estimation of ungaged inflow, calibration, and verification. The streamflow gages used for this study are illustrated in Figure 1. USGS streamflow gages on the mainstem Missouri River are listed in Table 1. Daily stages and flows are used in the UMRSFFS UNET hydraulic analysis.

Table 1. Missouri River Mainstem USGS Stream Gaging Stations

Station	River Mile Location	USGS Station Number	Gage Datum (feet, msl)
Rulo, NE	498.0	06813500	837.2
St. Joseph, MO	448.2	06818000	788.2
Kansas City, MO	366.1	06893000	706.4
Waverly, MO	293.5	06895500	646.0
Boonville, MO	196.6	06909000	565.4
Hermann, MO	97.9	06934500	481.6
St. Charles, MO (stage only)	28.1	06935965	413.5

Geometry. New mapping data was used to develop cross sections for the Missouri River mainstem reaches in the UNET model. Digital terrain models (DTMs), which cover the Missouri River floodplain from bluff to bluff, were produced from aerial photography obtained in the late 1990's. DTMs with soundings were produced by merging the DTMs with 1998 hydrographic survey data of the Missouri River channel. Missouri River cross sections were developed from this data.

Locations of Missouri River cross sections were laid out on digital USGS 1:24,000 scale quadrangle maps. Cross sections were laid out based on the geomorphology of the channel, attempting to capture locations of features such as pools and crossings. Cross sections averaged approximately 0.7 to 0.8 miles apart in rural areas and 0.2 to 0.3 miles apart in urban areas. For bridges, four cross sections were laid out -- two upstream and two downstream of each bridge. The cross section locations were stored in ArcView shape files. The cross section shape files and the DTMs with soundings were used to produce geo-referenced cross sections for the Missouri River.

In the UNET hydraulic model, there are twelve major tributaries of the Missouri River with USGS streamflow gages. These tributaries are illustrated in Figure 1 and are included as separate routing reaches in the UNET model. The tributary cross sections were developed from USGS 7.5 minute series quadrangle topographic maps. Tributaries are modeled from the last downstream USGS gaging station on the tributary to their confluence with the Missouri River. Tributary modeling is of limited detail and intended for inflow routing only.

Levee Data. Levees line the Missouri River banks, on one or both sides of the river, for virtually the entire length of the river from Rulo, Nebraska, to the confluence with the Mississippi River near St. Louis, Missouri. Levees impact hydraulics and flood routing in the UNET model. They are simulated within the UNET model as storage cells. When levees overtop and fill to overflowing during flood events, the UNET program switches from storage cells to overbank conveyance behind the levees. The program makes this switch based on a triggering discharge or elevation (UNET User's Manual 2001).

Levees are defined as cells in the levee file (also known as the "include" file). A levee cell may define either an individual levee, or a series of levees that are connected together in a continuous, unbroken line of protection. Levee properties such as top of levee elevation, levee upstream and downstream boundaries by river mile, breach elevation, etc., are the levee parameters included in the levee file for each levee. Also included for each levee is the discharge or elevation that will trigger overbank conveyance. Flood-fighting efforts, which entail increasing the effective levee height, were not considered for this analysis.

Development of the UNET model.

Current Conditions Model. The Missouri River current conditions UNET model was developed for the period of record analysis. The geometry of the model consists of the new bluff-to-bluff Missouri River cross sections, tributary cross sections, and levees as described previously. The cross sections are grouped into routing reaches in the cross section file. The mainstem routing reaches extend between tributary inflow points. Each tributary is a routing reach. Levee parameters are in the levee file. Inflow and stage data (input data) are accessed via the boundary conditions file. The input data is stored in data storage system files called "DSS" files. All input data for the period 01 January 1900 to 30 September 2000 were assembled into DSS files. All the geometry, boundary conditions, and data files described above were assembled and used for UNET simulations.

In the current conditions model, the Missouri River is modeled from Nebraska City, Nebraska, downstream to the mouth. This provides an overlap with the Omaha District UNET model of the Missouri River above the districts' common boundary at Rulo, Nebraska. The overlapping reach helps control computational instability associated with model boundary areas, and aid with convergence and transition at district boundaries.

Calibration. Following assembly of all the files and input data necessary to run a UNET model, the Kansas City District's Missouri River current conditions model was calibrated to daily flow and stage data for calendar year 1993. Initial attempts at calibrating the current conditions model using the automated techniques in UNET were unsuccessful. It was therefore necessary to calibrate the UNET model by adjusting roughness or Manning's *n* values, fine tuning of hydrographs using conveyance change factors, and adjusting levee parameters as necessary. The processes used in the calibration procedure for the current conditions model are described in the following paragraph.

The calibration procedure began with calculation of estimates of ungaged inflows for the 1993 time period. Estimates of ungaged inflow are computed using the Null Internal Boundary Condition (NIBC) feature of the UNET program (UNET User's Manual 2001). Then, the current conditions model was calibrated to the recorded high water marks for the flood of July-August 1993 by adjusting roughness values. Following initial calibration to high water marks, the model was further calibrated to the observed stage and flow hydrographs for the year 1993 at each of the six Kansas City District streamflow gages. This hydrograph calibration was accomplished using the discharge-vs.-conveyance option in UNET. Additionally, the seasonal conveyance change option was utilized to account for the change in Manning's *n* value due to temperature (UNET User's Manual 2001). Levee hydrographs were examined to verify that the levees performed as they had during the flood of 1993. Levee parameters were adjusted where necessary to replicate levee performance of the flood of 1993.

Period of Record Analysis.

Computation of Ungaged Lateral Inflow. Ungaged tributary inflow and other sources of ungaged inflow for the period of record must be computed before the period of record analysis can be performed. Estimates of ungaged lateral inflow were computed using the Null Internal Boundary Condition (NIBC) feature of the UNET program (UNET User's Manual 2001). For the Missouri River, ungaged lateral inflow was developed using three different Missouri River UNET models, one for each of the following time periods – 1900 through 1940, 1940 through 1961, and

1961 through 2000. These three models had been previously assembled for this and earlier studies.

To calculate the ungaged inflow, each UNET model was automatically calibrated using rating curves at the mainstem USGS gaging stations. The exception was the St. Charles gage, which is a stage gage in the backwater of the Mississippi River. Rating curves were derived for the gages from the observed data. The automatic calibration routine of the UNET program derived the rating curves and calibrated each model by adjusting the rating curves to reproduce stage at the USGS gages, based on observed flows. Then the NIBC feature in UNET was used to compute estimates of ungaged lateral inflow throughout each model by optimizing to USGS observed flow (UNET User's Manual 2001).

The computed ungaged lateral inflows for 1900 through 2000 produced by this procedure were merged into one DSS file. This file served as an input flow file for the period-of-record analysis. In the boundary conditions file of the Missouri River current conditions model, the ungaged inflows were distributed between the principal gaging stations based on average flow at the tributary gages.

Period of Record Analysis. The period of record analysis was performed with the current conditions UNET model to establish the rating curves at each mainstem Missouri River cross section in the geometry file. This model had been calibrated to the 1993 flood, as described previously. Daily flow data was analyzed for the time period 01 January 1900 to 30 September 2000. In effect, this process predicts how the river, in its present configuration, would respond to the historic inflows to the river. The period of record execution of the UNET model was performed several times, first with the observed USGS flow record, and finally with the regulated flow data set developed by the hydrologic analyses of this study. The UNET program computes daily stages and flows at all cross sections for the period of record. Results from the UNET program computations include annual maximum flows and annual maximum stages at each Missouri River cross section in the model. From this data, the rating curve for each Missouri River cross section was developed.

Water Surface Profile Analysis.

Development of UNET-Based Flood Frequency Profiles. In order to develop the hydraulic analysis programs required for modeling the Missouri River, a unique version of UNET was developed by Dr. Robert Barkau for the Kansas City District. Dr. Barkau supplemented this version of UNET with an EXCEL spreadsheet file that contained specialized macros. When the period-of-record discharges are run in this special version of UNET, a trigger in the boundary conditions file causes the following steps to be initiated within the UNET program for each mainstem cross section:

1. A tabulation of annual maximum flow for the period of record, and its associated stage (from that same day) is produced at each cross section in the cross section file. Also, a tabulation of maximum annual stage and its associated discharge is created for each cross section.

2. For the rating curve for each cross section, these two data sets are combined into a single file and then plotted. A polynomial curve is passed through

the data cluster, and the coefficients for this equation are read out into the referenced EXCEL file. A standard error between the "observed" USGS discharges and discharges computed from the equations is provided. The discharge-vs.-stage points estimated for each rating curve are then read as paired data points into a DSS file. The pathnames of the rating curves become a part of an EXCEL importable file.

3. Additional data is generated in the UNET file to estimate peak discharges and peak stages on a frequency basis. These flow and stage data are generated using both Weibull and Pearson III techniques. Polynomial equations are developed for each of these curves. Computed ordinates from each curve can be created from these equations. These curves are read into DSS files as paired data points, and their DSS pathnames are exported to an EXCEL readable file.

In the case of the Missouri River, the observed USGS discharge data for the period of record contain some historic high peak flood flows. Therefore, a full definition of the rating curve is produced using this flow set for most reaches of the river. On the other hand, the regulated flow set, because it contains the effects of the flood control reservoir system, provides better estimates of current stage-probability and discharge-probability curves. Thus, the regulated flow set provides an avenue for verifying the frequency flow estimates developed by the Hydrology study phase of UMRSFFS.

After the UNET runs were made for the period-of-record, the rating curves for each Missouri River cross section, in the form of exponents for polynomial equations, were exported to the special EXCEL spreadsheet. The discharges from the Hydrology study phase of UMRSFFS for the various frequency floods were listed on this spreadsheet by cross section. Each sheet in this EXCEL file was allocated to a single flood frequency. Upon execution of the spreadsheet macro, the elevation at each cross section for each frequency flood was determined. These elevations were exported to another spreadsheet for further editing. Additional editing was required upstream of major river junctions, in the "crossover" area on the lower river, and in the Rulo area at the junction of the Omaha and Kansas City Districts.

Large River Confluences. Development of UNET-based flood frequency profiles presents a special problem at river junctions. This is due to the backwater effects built into the historic record at that junction. It is noteworthy that the rating curves downstream of the junction are quite smooth, with all of the data points closely clustered around the fitted curve. The plotted rating curves upstream of the junction exhibit a wide scatter, with the fitted curve drawn through the middle of the data cluster. It is also worthwhile to note that the stage-probability curves, both downstream and upstream of the junction, exhibit data points tightly clustered around the computed curve, with no appreciable data scatter. Since smooth profile surfaces at these junctions are observed physical phenomena, and are therefore expected in the final publication of these profiles, a supplemental methodology is proposed for the junction areas.

When discontinuous profiles are encountered due to backwater effects at stream junctions, then the stage-probability curve from the regulated flow period-of-record run can be used to guide the drawing of a line in the upstream rating curve. In effect, this is a "supplemental" rating curve. This supplemental line must be contained within the scatter of data points for the rating curve. This must be done for several upstream cross sections, depending on the length of the backwater effects. It is possible to use some of the editing capacity of the UNET program's UNETPLOT utility feature for this purpose. For these profiles, however, all editing was done in a secondary EXCEL spreadsheet. It is noted that each revised rating curve must fit somewhere within the data cluster for a particular cross section. This assures that we are working within the natural hydrologic characteristics and capacities of the system.

The probability of coincident frequency floods occurring both upstream and downstream of a significant stream junction is small. Therefore, these circumstances are probably not reflected in the historical record at the junction. The flood frequency profiles commonly published through stream junctions, however, are based on this assumption, and are therefore not quite realistic. It is further noted that the utility provided by employing this assumption, in most cases, far outweighs the weakness of the underlying hydrology. The assumption that the same frequency flood occurs at the same time both upstream and downstream of the junction is unrealistic. Thus, the employment of a non-central supplemental rating curve in these junction areas is justified. This supplemental methodology is quite useful in the Missouri-Mississippi crossover area and at other major river junctions.

As an example of the difference between rating curves downstream and upstream of a major river junction, data for two representative Missouri River cross sections straddling the mouth of the Kansas River are appended. Figure 2 is the computed rating curve for the Missouri River cross section at RM 367.4, which is immediately downstream of the mouth of the Kansas River. Note that this curve fits smoothly within the very regular data cluster. Contrast that curve with that data associated with rating curve shown on Figure 3, for the cross section at RM 370.26. This cross section is a few miles upstream of the mouth of the Kansas River. This data is less regular, due to the backwater effects from the Kansas River. Note the high-stage/low-discharge point caused by the 1951 flood. This was a serious event on the Kansas River, but was of a much lesser magnitude on the Missouri River upstream of the junction.

These backwater effects manifest themselves upstream of most of the major tributaries, and they are particularly severe upstream of the mouths of the Kansas and Osage Rivers. Fortunately, the Kansas City District has recently developed detailed HEC-RAS models in these areas. These HEC-RAS models use the same geometry and discharges that were used in the UNET period-of-record analysis, and were calibrated to the 1993 high water marks. The profiles computed by HEC-RAS were used to finalize the profiles in these backwater reaches. This was done within the secondary EXCEL spreadsheet.

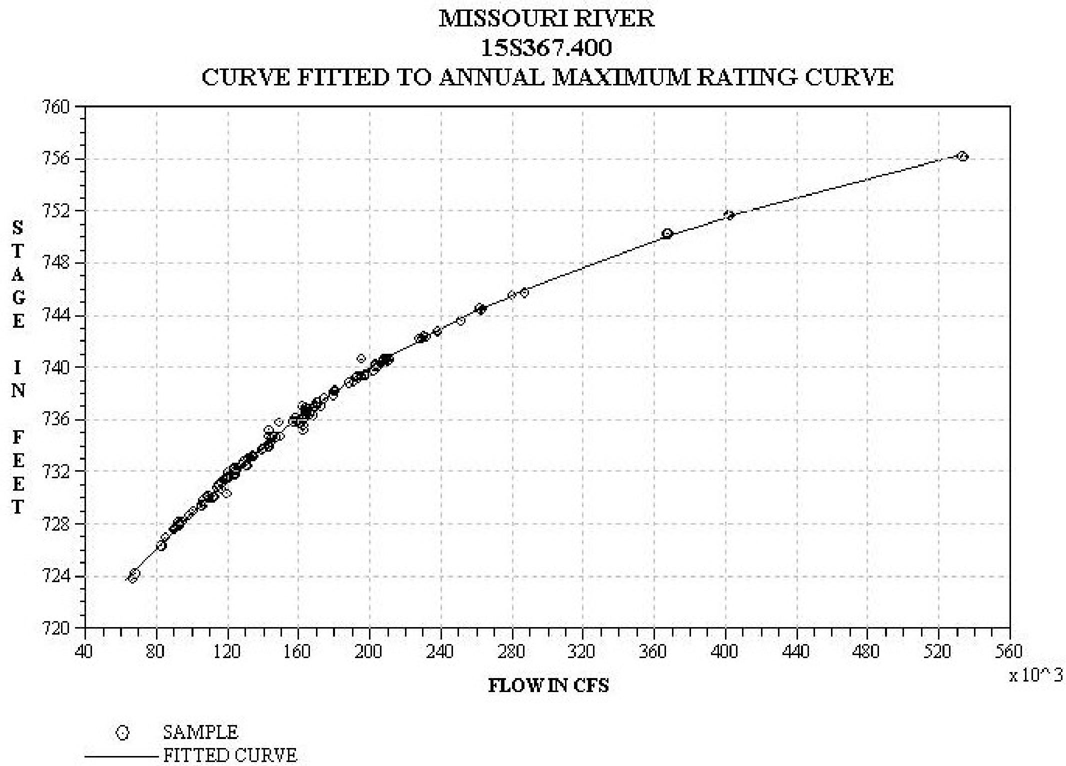

Figure 2. Missouri River Rating Curve, downstream of the Kansas River

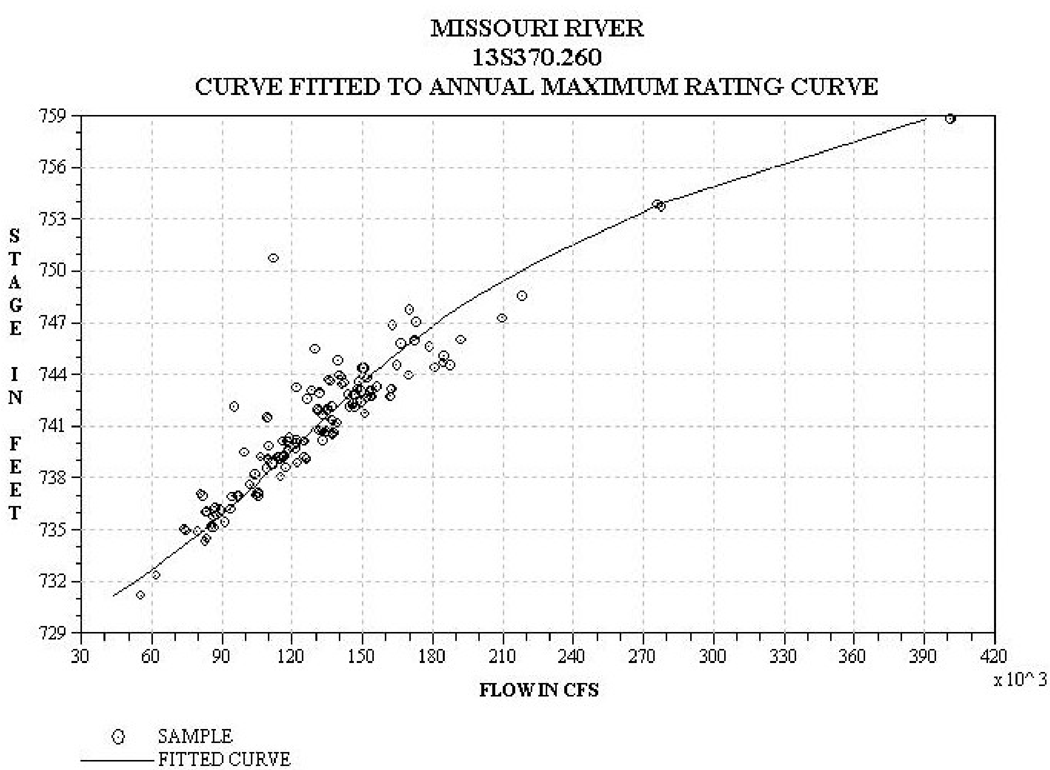

Figure 3. Missouri River Rating Curve, upstream of the Kansas River

Final Profile Processing. The final two steps in processing the flood profiles were to utilize a five-point, distance-weighted, profile smoothing technique developed by the Rock Island District, and then to interpolate the profiles to whole river miles. This latter step was undertaken because the previous set of flood profiles was published circa 1976 at whole river mile intervals.

Conclusions

Comparison with Previous Study. The study described herein supercedes the water surface profiles produced by the Kansas City District circa 1976. A one-dimensional steady state computer program developed by the Kansas City District, which is known as KCD Backwater, produced those profiles. This program is no longer in use. A comparison of the predicted water surface elevations from this study and the previous one is listed below for the six Missouri River mainstem gaging stations.

Table 2. Profile Comparison

		Elevation (feet, msl)		
Gage	Flood	ca 1976 Profile	2003 Profile	Difference (ft)
Rulo NE	10-Year	861.2	860.1	-1.1
	100-year	861.6	863.0	+1.4
St Joseph MO	10-Year	811.3	813.5	+2.2
	100-Year	815.1	819.4	+4.3
Kansas City MO	10-Year	741.2	740.1	-1.1
	100-Year	748.5	749.5	+1.0
Waverly MO	10-Year	674.4	674.4	0.0
	100-Year	677.6	677.5	-0.1
Boonville MO	10-Year	596.6	594.7	-1.9
	100-Year	599.9	601.9	+1.0
Hermann MO	10-Year	513.7	512.5	-1.2
	100-Year	518.4	518.6	+0.2

Study Limitations. This study represents the best overall estimates available at this time of the water surface elevations that are associated with the various frequency floods on the Missouri River. The results of the study are subject to the uncertainties normally associated with these types of profiles. The Kansas City District profiles are heavily predicated on the performance of the various Federal and non-Federal levees that line the river throughout the district. When, where, and how these individual levees perform during high flow events has a major local influence on these profiles.

References

Barkau, R. L. UNET: Unsteady Flow through a Full Network of Open Channels, February 24, 1992.

U. S. Army Corps of Engineers, Hydrologic Engineering Center. UNET: One-Dimensional Unsteady Flow Through a Full Network of Open Channels, User's Manual, April 2001.

Additional Information

Barkau, R. L. Impact of Levees on the Middle Mississippi River: A report prepared for the Strategic Assessment and Strategy Team, July 15, 1994.

Interagency Floodplain Management Review Committee. Sharing the Challenge: Floodplain Management into the 21st Century, June 1994.

U. S. Army Corps of Engineers. Floodplain Management Assessment of the Upper Mississippi and Lower Missouri Rivers and Their Tributaries, Appendix A (Hydraulic Modeling), June 1995.

U. S. Army Corps of Engineers, Kansas City District. The Great Flood of 1993 Post-Flood Report: Lower Missouri River Basin, Appendix E, September 1994.

U. S. Army Corps of Engineers, Omaha District. The Great Flood of 1993 Post Flood Report: Lower Missouri River Basin, Appendix D, September 1994.

U. S. Army Engineer District, Kansas City, Corps of Engineers. Missouri River Basin, Kansas and Missouri: Design Memorandum No. 1A, Preliminary Master Plan, March 1964.

U. S. Army Engineer District, Kansas City, Corps of Engineers. Missouri River Restudy, Missouri River Backwater Computations, 1977 through 1979.